

Project Final Presentation

BORON REJECTION BY REVERSE OSMOSIS MEMBRANES: NATIONAL RECONNAISSANCE AND MECHANISM STUDY – PHASE I



Agreement No. 04-FC-81-1050
Desalination and Water Purification Research and Development Program

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Background

- Sea water – the largest source of water
- High salt concentration hampering utilization of sea water
- Sea water as the water source
 - Due to the localized scarcity and the deterioration of the raw water quality

Boron Problem

- **Boron**
 - Average 4.6 ppm in sea water
 - Indispensable for the organism growth
- **Boron problem**
 - Excessive exposure can bring
 - i) Massive leaf damage and premature ripening for plants
 - ii) Inhibition of male reproductive capability
 - Current WHO drinking water guideline of boron is 0.5 ppm
 - Only 70 to 80 % removal of boron in Sea Water Reverse Osmosis (SW RO) membrane plant → Most of the existing plant cannot meet the guideline

Objectives

- To understand the mechanism of boron rejection by and transport through RO membranes and elucidate the effects of operating condition such as pH and temperature on boron transport
- To characterize ambient boron concentrations in various water bodies and assess removal of boron at existing RO facilities
- To identify appropriate RO configurations to meet target boron concentration and develop associated cost estimates for full-scale installation and operation

PART I. NATIONAL RECONNAISSANCE STUDY

Operating Conditions of Desalination Plants

Plant	Location	Feed water	Membrane array	Model, Manufacturer	Pressure	Permeate Flow rate	Recovery
A	Carlsbad, CA	Sea water (Pacific)	Single pass	SWC3, Hydranautics	810psi	17.2gpm	50%
B	Abila Beach, CA	Sea water (Pacific)	Double pass	FT30, Dow (Filmtec)	880psi	225gpm	45%
C	Corte madera, CA	Sea water (Pacific)	Single pass	TM820A-400, Toray	560psi	2.5gpm	40%
				SW30HR LE-400, Dow (Filmtec)	660psi	2.9gpm	40%
				SWC4+, Hydranautics	545psi	2.2gpm	40%

Operating Conditions of Desalination Plants (Cont'd)

D1	Cayman island	Sea water (Atlantic)	Double pass (Sampling performed after the first pass)	SWHR30-380, Dow (Filmtec)	802psi	574gpm	38%
D2				SWHR30-380, Dow (Filmtec)	966psi	455gpm	40%
D3				SWHR30-380, Dow (Filmtec)	945psi	321gpm	42%
E	El Segundo, CA	Brackish water	Single pass	ESPA2, Hydranautics	245psi	1450gpm	85%
F	Venice, FL	Brackish groundwater	Single pass	8821 TFC HR, Fluid systems	161psi	750gpm	50%
G	Mountain Pleasant SC	Brackish groundwater	Double pass	ESPA1&2, Hydranautics	125psi	400gpm	80%
			Double pass	ESPA1&2, Hydranautics	145psi	350gpm	80%
			Double pass	ESPA1&2, Hydranautics	125psi	500gpm	80%
			Double pass	ESPA1&2, Hydranautics	125psi	486gpm	80%

Results of Analysis: Cold Season

		pH	Conductivity	B	Na	Mg	Ca	Cl	SO ₄
A	Feed	6.69	56400	4.46	11462	1140	378	16856	2104
	Concentrate	-	106600	7.32	26295	2339	769	35269	4612
	Permeate	5.33	387	1.36	75.02	0.54	0.18	92.56	1.65
	Rejection	-	99.31	69.54	99.35	99.95	99.95	99.45	99.92
E	Feed	6.24	1186	0.48	640	23.5	60.28	112.1	224.7
	Concentrate	-	6900	1.47	1492	177.5	461	724.4	1936
	Permeate	6.32	23.10	0.24	12.81	0.025	0.022	ND	ND
	Rejection	-	98.05	49.17	98	99.89	99.96	100	-
F	Feed	7.10	3570	0.11	669	159.5	412.6	407.2	1556
	Concentrate	-	6290	0.15	1492	311.5	806.4	781.6	3011
	Permeate	6.04	38	0.051	25.52	0.17	0.44	2.97	3.15
	Rejection	-	98.94	53.20	96.19	99.89	99.89	99.27	99.80

Results of Analysis: Cold Season (Cont'd)

G Train 1	Feed	8.31	1713	2.88	688	0.44	1.44	112.6	ND
	Concentrate	-	7420	2.04	2802	1.25	4.32	502.1	ND
	Permeate	8.13	89.10	3.39	45.36	0.024	0.028	ND	ND
	Rejection	-	94.80	-17.76	93.41	94.47	98.03	100	-
G Train 2	Feed	8.55	1615	2.66	707	0.32	1.19	98.84	ND
	Concentrate	-	6070	2.91	2513	0.96	3.68	378.2	ND
	Permeate	8.35	120.80	3.16	33.42	0.019	0.011	ND	ND
	Rejection	-	92.52	-18.88	95.28	94.09	99.07	100	-
G Train 3	Feed	8.4	1760	3.01	900	0.38	1.46	118.8	ND
	Concentrate	-	7420	2.31	2552	1.20	4.56	521.7	ND
	Permeate	8.16	98.10	2.56	33.23	0.025	0.022	ND	ND
	Rejection	-	94.43	15.17	96.31	93.37	98.48	100	-
G Train 4	Feed	8.35	1827	3.37	842	0.49	1.56	119.3	ND
	Concentrate	-	7580	2.83	2552	1.50	4.91	506.7	ND
	Permeate	8.06	184.90	3.00	25.91	0.025	0.029	ND	ND
	Rejection	-	89.88	10.99	96.93	94.90	98.11	100	-

Results of Analysis: Hot Season

	Plant	pH	Conductivity	B	Na	Mg	Ca	Cl	SO ₄
A	Feed	8.03	50700	4.00	9780	609.5	1182	18968	2569
	Concentrate	-	91500	7.05	19597	806.1	1767	32644	4603
	Permeate	6.58	510	1.17	70.23	0.51	1.50	142.26	4.94
	Rejection	-	98.99	70.55	99.28	99.92	99.87	99.25	99.81
B	Feed	8.2	49740	4.19	10434	614.4	1190	19183	2606
	Concentrate	-	76000	7.18	27384	791.0	1745	32123	4773
	Permeate	7.4	570	0.82	85.23	1.38	4.60	158.47	10.61
	Rejection	-	98.85	80.43	99.18	99.78	99.61	99.17	99.59
C (Conventional Pretreatment)	Feed	8.01	42580	3.62	7864	567.20	1049	15970	2112
	Concentrate	-	-	-	-	-	-	-	-
	TM820A Permeate	7.73	320	1.13	49.30	0.44	1.78	92.94	5.40
	LE Permeate	7.56	220	0.61	32.34	0.21	1.05	65.98	4.04
	SWC4+ Permeate	7.74	100	0.52	29.12	ND	0.12	33.19	2.28
	TM820A Rejection	-	99.47	68.81	99.37	99.92	99.83	99.42	99.74
	LE Rejection	-	99.64	82.93	99.59	99.96	99.90	99.59	99.81
	SWC4+ Rejection	-	99.83	85.42	99.63	100.00	99.99	99.79	99.89

Results of Analysis: Hot Season (Cont'd)

C (Membrane Pretreatment)	Feed	7.5	43054	3.64	8340	573.90	1053	15884	2115
	Concentrate	-	-	-	-	-	-	-	-
	TM820A Permeate	6.00	240	0.99	45.82	0.21	1.08	68	5
	LE Permeate	6.02	180	0.54	39.43	ND	0.43	50.13	2.63
	SWC4+ Permeate	6.06	150	0.70	19.88	ND	0.09	41.99	2.28
	TM820A Rejection	-	99.60	72.74	99.45	99.96	99.90	99.57	99.77
	LE Rejection	-	99.70	85.16	99.53	100.00	99.96	99.68	99.88
	SWC4+ Rejection	-	99.75	80.73	99.76	100.00	99.99	99.74	99.89
D1	Feed	7.03	54880	4.73	12838	626.2	1153	18509	2551
	Concentrate	-	81580	7.32	29592	733.7	1478	25882	3859
	Feed End Permeate	5.80	375	0.78	60.32	0.44	1.63	100.25	5.76
	Brine End Permeate	5.97	886	1.55	157.4	1.18	3.74	255.31	9.22
	Feed End Rejection	-	99.55	83.52	99.53	99.93	99.86	99.46	99.77
	Brine End Rejection	-	98.94	67.19	98.77	99.81	99.68	98.62	99.64

Results of Analysis: Hot Season (Cont'd)

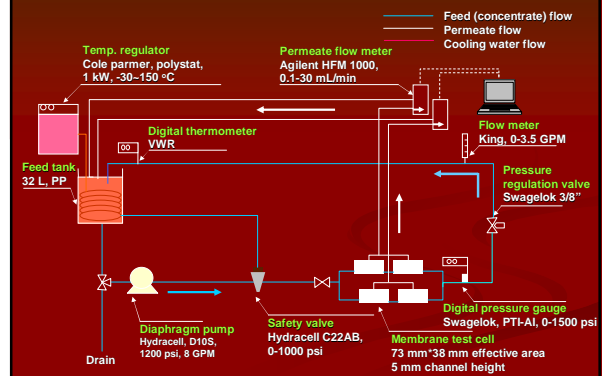
D2	Feed	7.18	52410	4.51	11004	641.6	1197	18996	2563
	Concentrate	-	83550	7.07	28304	830.5	1735	32440	4479
	Feed End Permeate	6.42	464	0.85	47.48	0.91	2.79	124.03	16.48
	Brine End Permeate	6.39	2198	1.56	301.3	8.93	29.43	657.64	75.13
	Feed End Rejection	-	99.48	81.01	99.57	99.86	99.77	99.35	99.36
	Brine End Rejection	-	97.55	65.27	97.26	98.61	97.54	96.54	97.07
	Feed	7.19	50380	4.67	12304	615.4	1173	18869	2598
	Concentrate	-	83390	6.97	30302	747.6	1575	28359	3928
D3	Feed End Permeate	6.56	334	0.94	45.39	0.23	1.11	87.18	11.41
	Brine End Permeate	6.27	2651	1.59	402.3	10.87	37.20	783.17	87.58
	Feed End Rejection	-	99.64	79.87	99.63	99.96	99.91	99.54	99.56
	Brine End Rejection	-	97.11	65.95	96.73	98.23	96.83	95.85	96.63

Results of Analysis: Hot Season (Cont'd)

E	Feed	6.32	1429	0.71	537	96.95	86.90	168	213
	Concentrate	-	8805	2.11	1104	248.9	155.5	780	1445
	Permeate	5.27	38.05	0.35	9.34	ND	ND	2.33	0.24
	Rejection	-	97.34	50.43	98.26	100.00	100.00	98.61	99.89
F	Feed	7.06	4775	0.12	901	326.2	173.6	320	1430
	Concentrate	-	10380	0.19	1932	535.8	256.5	566	2853
	Permeate	6.09	40.05	0.04	12.01	0.36	0.10	3.79	6.70
	Rejection	-	99.16	67.83	98.67	99.89	99.94	98.82	99.53

PART II. MECHANISTIC STUDY ON BORON TRANSPORT THROUGH REVERSE OSMOSIS MEMBRANE

Membrane Test Unit



Experimental Condition

Membranes (From the manufacturers' specification)

Maker	Sachan	Hydranautics	Dow (Filtmtec)	Dow (Filtmtec)	Toray	Toray
Model	SR	SWC4+	SW30 HR XLE	SW30 HR LE	TM820	TM820A
Material	Polyamide composite	Polyamide composite	Polyamide composite	Polyamide composite	Polyamide composite	Polyamide composite
Rejection*	99.6%	99.8%	99.7%	99.75%	99.75%	99.75%
Flux* * (gal/ft ² -d)	15.8	17.1	22.5	18.8	16.5	15

+ Test condition: 25°C, 800psi, 32,000 ppm NaCl solution

* Calculated based on the permeate flow rate and the membrane area of the module

Feed solution (Synthetic sea water)

10,500mg/L Sodium, 19,000mg/L Chloride, 1,350mg/L Magnesium, 450 mg/L Calcium, 2,700mg/L Sulfate, and 5mg/L Boron

Experimental Condition (Cont'd)

Operating condition

Membrane cell dimension: 73 mm length × 38 mm width × 5 mm height
 Feed volume: 21.8 L
 Flow rate: 1.89 LPM (0.5 GPM) per cell
 Cross flow velocity: 0.17 m/s

Experimental Scheme

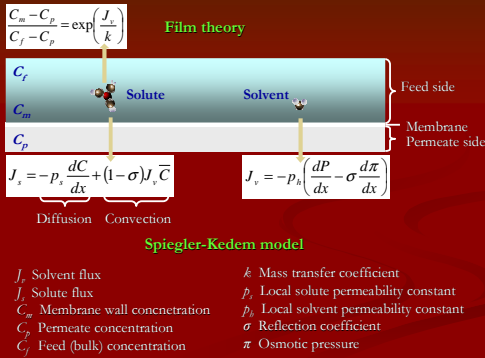
pH effect experiment

6 membranes tested
 Temperature fixed at 25 °C
 Experiment Performed based on the orthogonal matrix between pH (6.2, 7.5, 8.5, 9.5) and Pressure (600, 700, 800, 900, 1000 psi)

Temperature effect experiment

4 membranes tested
 pH fixed at 6.2 and 9.5
 Experiment Performed based on the orthogonal matrix between Temperature (15, 25, 35 °C) and Pressure (600, 700, 800, 900, 1000 psi)

Membrane Transport Model (Spiegler-Kedem Model with Film Theory)



Membrane Transport Model (Cont'd)

Basic equations

- Spiegler-Kedem model

$$J_s = -p_s \frac{dC}{dx} + (1 - \sigma) J_v \bar{C} \quad \text{Equation 1}$$

$$J_v = -p_s \left(\frac{dP}{dx} - \sigma \frac{d\pi}{dx} \right) \quad \text{Equation 2}$$

- Film theory

$$\frac{C_m - C_p}{C_f - C_p} = \exp\left(\frac{J_s}{k}\right) \quad \text{Equation 3}$$

The governing equation for the solute transport (Equation 1+3)

$$\frac{R_0}{1 - R_0} = \frac{C_f - C_p}{C_p} = \frac{\exp\left(\frac{J_s}{k}\right) [1 - \exp(-J_v \cdot (1 - \sigma) / P_s)] \exp(J_s / k)}{1 - \sigma}$$

$$R_0 \text{ Apparent rejection} = (C_f - C_p) / C_f$$

Need to determine k , P_s , σ to predict the solute transport

Parameter Estimation

The governing equation of solutes transport

$$\frac{R_0}{1 - R_0} = \frac{C_f - C_p}{C_p} = \frac{\sigma}{1 - \sigma} [1 - \exp(-J_v \cdot (1 - \sigma) / P_s)] \exp(J_s / k)$$

Experimental evaluation of mass transfer coefficient (k) of salt (from Equation 2 and 3 in previous slide)

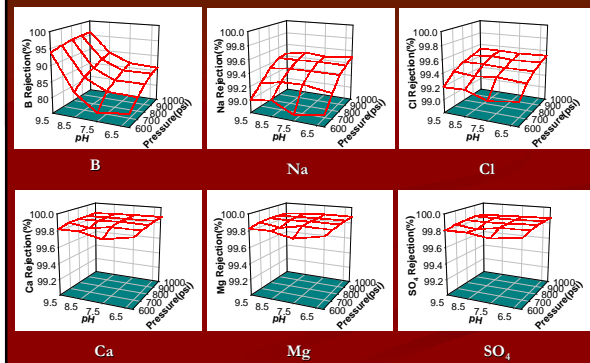
$$k = \frac{J_s(\text{Salt})}{\ln \left[\frac{\Delta P}{\pi_s - \pi_p} \left(1 - \frac{J_s(\text{Salt})}{J_s(H_2O)} \right) \right]}$$

Evaluation of mass transfer coefficient (k) of boron

$$\frac{k_{\text{Salt}}}{k_{H_2O}} = \left(\frac{D_{\text{Salt}}}{D_{H_2O}} \right)^\beta$$

Evaluation of P_s and σ from non-linear regression using experimental data set between J_v vs $R_0 / (1 - R_0)$

Effect of pH and Pressure on Solute Rejection (SR)



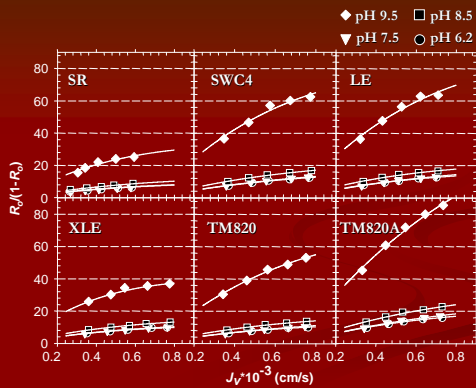
Estimated SKF Model Parameters of Boron for pH Effect Experiment

	pH	6.2	7.5	8.5	9.5
SR	k (cm/s)	0.00184	0.00168	0.00203	0.00178
	σ (-)	0.9753	0.994	0.9905	0.9933
	$P_{s,B}$ (cm/s)	5.47E-05	6.11E-05	4.65E-05	1.40E-05
	R^2	0.9877	0.9867	0.9951	0.9319
SWC4+	k (cm/s)	0.00238	0.00236	0.00286	0.00274
	σ (-)	0.9832	0.9918	0.9858	0.9957
	$P_{s,B}$ (cm/s)	3.84E-05	3.92E-05	2.84E-05	7.24E-06
	R^2	0.9951	0.9971	0.9956	0.9701
XLE	k (cm/s)	0.00265	0.00262	0.00269	0.00242
	σ (-)	0.962	0.9696	0.9766	0.9878
	$P_{s,B}$ (cm/s)	4.15E-05	4.21E-05	3.24E-05	9.48E-06
	R^2	0.9923	0.9949	0.9928	0.9836
LE	k (cm/s)	0.00207	0.00208	0.00244	0.00238
	σ (-)	0.9821	0.9931	0.9876	0.9976
	$P_{s,B}$ (cm/s)	3.33E-05	3.61E-05	2.51E-05	6.82E-06
	R^2	0.9921	0.9942	0.9872	0.9747

Estimated SKF Model Parameters of Boron for pH Effect Experiment (Cont'd)

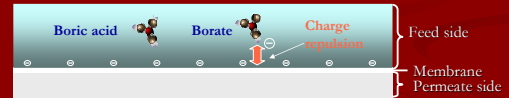
TM820	k (cm/s)	0.00182	0.0018	0.00217	0.00205
	σ (-)	0.9812	0.9986	0.9935	0.9989
	$P_{s,B}$ (cm/s)	4.36E-05	4.74E-05	3.40E-05	8.93E-06
	R^2	0.9847	0.9971	0.9956	0.9943
TM820A	k (cm/s)	0.0025	0.0025	0.00307	0.00285
	σ (-)	0.9819	0.9912	0.9928	0.9992
	$P_{s,B}$ (cm/s)	2.76E-05	2.85E-05	2.11E-05	6.07E-06
	R^2	0.9904	0.9917	0.9846	0.9922

Boron Experimental Data vs SKF Model Fit (pH Effect Experiment)



Effect of pH on Boron Transport Parameters

- The boron rejection was largely dependent on pH
- RO membrane surfaces had **negative charge** for all the pH range
- In the natural condition, boron exists as either **boric acid (H_3BO_3)** and borate ($H_2BO_3^-$)



- Higher rejection (less solute transport) in high pH \rightarrow due to the enhanced charge repulsion from the change of the boric acid species

Effect of pH on Boron Transport Parameters (Cont'd)

- From the previous argument, the following equations considering contribution from boric acid and borate separately were developed

$$P_{s,B} = \alpha_0 \times P_{s,(H_3BO_3)} + \alpha_1 \times P_{s,(H_2BO_3^-)}$$

$$\sigma_B = \alpha_0 \times \sigma_{(H_3BO_3)} + \alpha_1 \times \sigma_{(H_2BO_3^-)}$$

[Subscript] B : Boron (overall), H_3BO_3 : Boric acid, $H_2BO_3^-$: Borate

From Riley and Skirow (1975)

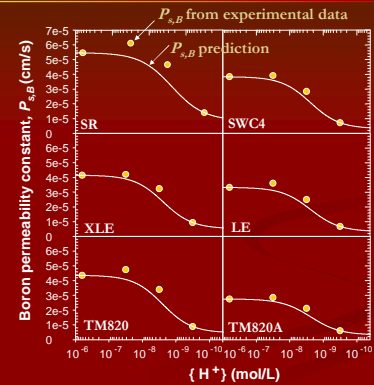
$$\alpha_0 = \frac{[H^+]}{[H^+] + K_{a1}} = \frac{[H_3BO_3]}{C_{T,B}} \quad \alpha_1 = \frac{K_{a1}}{[H^+] + K_{a1}} = \frac{[H_2BO_3^-]}{C_{T,B}} = 1 - \alpha_0$$

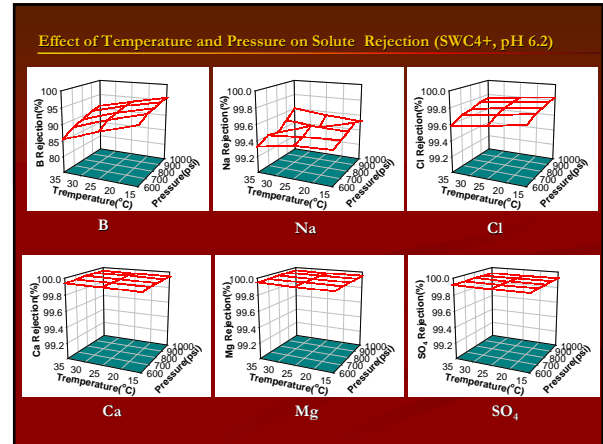
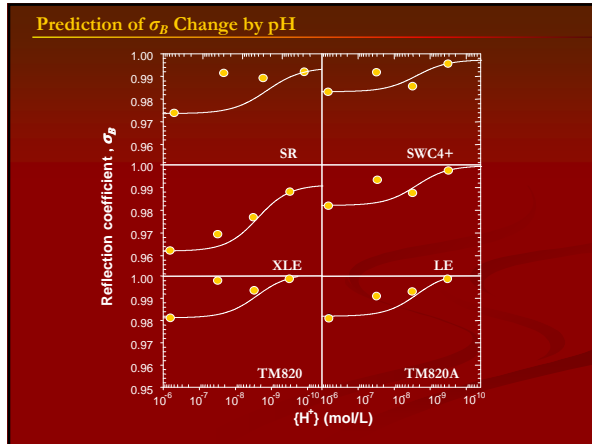
$$\text{where, } K_{a1} = \frac{[H_2BO_3^-][H^+]}{[H_3BO_3]}$$

$$-\log K_{a1} = \frac{2291.9}{T} + 0.01756 - 3.385 - 0.32051 \times C^{1/3} \quad (\text{Gieskes, 1974})$$

- $P_{s,(H_3BO_3)}$ and $P_{s,(H_2BO_3^-)}$ can be calculated from $P_{s,B}$ at two known pH
- In this study, $P_{s,B}$ at pH 6.2 and 9.5 were chosen
- $\sigma_{(H_3BO_3)}$ and $\sigma_{(H_2BO_3^-)}$ were calculated from the same way

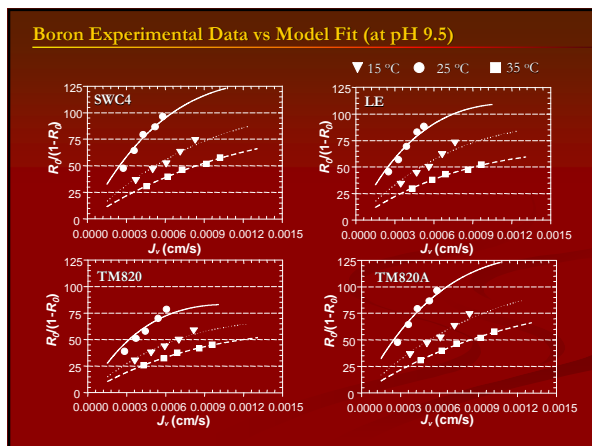
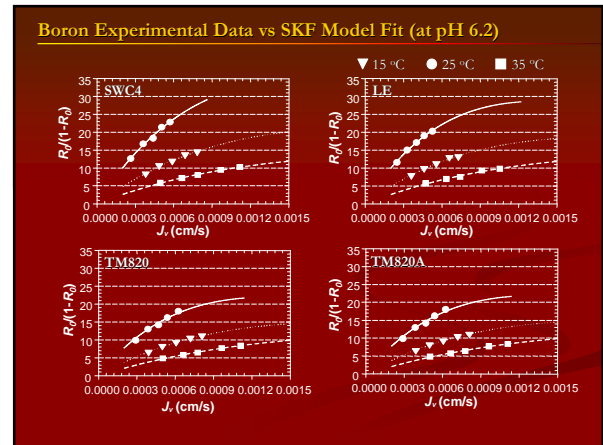
Prediction of $P_{s,B}$ Change by pH





Estimated Boron transport Parameters for Temperature Effect Experiment

		pH 6.2			pH 9.5		
		15°C	25°C	35°C	15°C	25°C	35°C
SWC4	k (cm/s)	0.00170	0.00258	0.00381	0.00177	0.00268	0.00396
	σ_B (-)	0.9997	0.9943	0.9826	0.999	0.999	0.9974
	P_{LB} (cm/s)	1.77E-05	3.69E-05	6.97E-05	4.19E-06	8.29E-06	1.24E-05
LE	k (cm/s)	0.00154	0.00234	0.00346	0.00140	0.00212	0.00313
	σ_B (-)	0.9968	0.9917	0.9861	0.999	0.999	0.996
	P_{LB} (cm/s)	1.73E-05	3.63E-05	7.00E-05	4.00E-06	7.60E-06	1.16E-05
TM820	k (cm/s)	0.00137	0.00208	0.00308	0.00120	0.00182	0.00269
	σ_B (-)	0.999	0.9967	0.9953	0.999	0.999	0.9971
	P_{LB} (cm/s)	2.23E-05	4.75E-05	8.93E-05	4.72E-06	9.04E-06	1.35E-05
TM820A	k (cm/s)	0.00194	0.00294	0.00435	0.00169	0.00256	0.00378
	σ_B (-)	0.9956	0.9956	0.9934	0.999	0.999	0.998
	P_{LB} (cm/s)	1.26E-05	2.73E-05	5.14E-05	3.05E-06	5.97E-06	8.76E-06



Prediction of Boron Transport Parameters Change by Temperature

- From the research with NaCl solution, the following correlations on the temperature and transport parameters were suggested (Sourirajan, 1970)

$$k \propto \exp(0.005T)$$

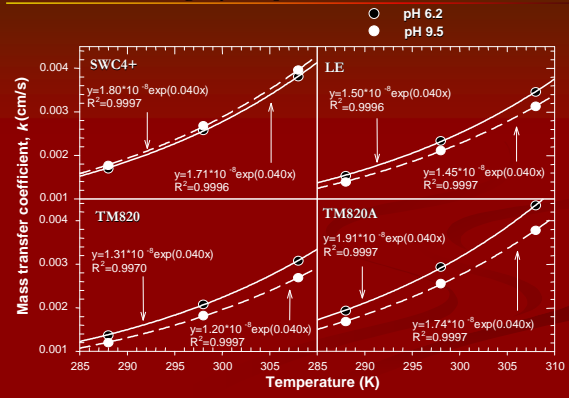
$$\left(\frac{D_{AM}K}{\Delta x}\right) \propto \exp(0.005T)$$
- Considering 1) similarity between $D_{AM}K/\Delta x$ and P_3 and 2) difference in the solute, following equations were suggested

$$k = k_0 \exp(a(T - T_0))$$

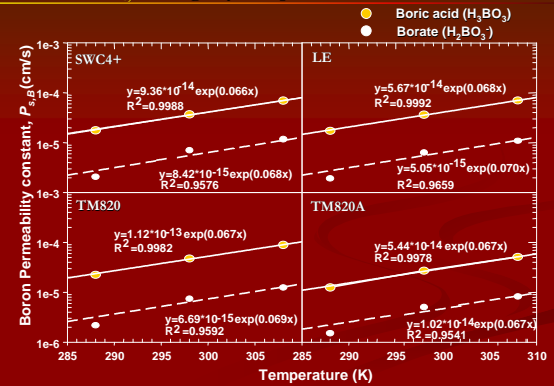
$$P_{s(H_2BO_3)} = P_{s(H_2BO_3)_0} \exp(b(T - T_0)) \quad P_{s(H_2BO_3^-)} = P_{s(H_2BO_3^-)_0} \exp(c(T - T_0))$$

$$\sigma_{(H_2BO_3)} = \sigma_{(H_2BO_3)_0} \exp(d(T - T_0)) \quad \sigma_{(H_2BO_3^-)} = \sigma_{(H_2BO_3^-)_0} \exp(e(T - T_0))$$
- * Subscript 0 means transport parameter at Temperature T_0
- After calculating transport parameters at each temperature, the unknowns (a, b, c, d, e) in the equations were obtained from the non-linear regression

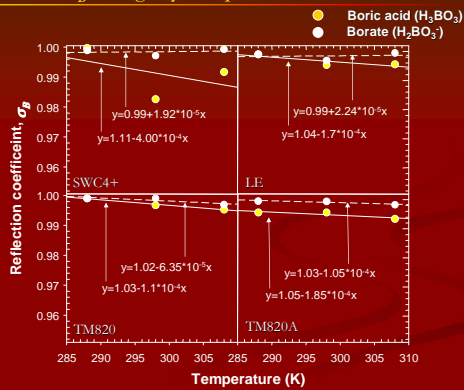
Prediction of k Change by Temperature



Prediction of $P_{s,B}$ Change by Temperature



Prediction of σ_B Change by Temperature



Equations for the Transport Parameter Estimation

Boron mass transfer coefficient

$$k = k_0 \exp(0.04(T - T_0))$$

Boron permeability constant

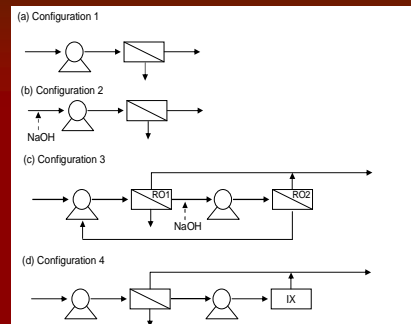
$$P_{s,B} = \alpha_0 \times P_{s(B,BO_3)_0} \exp(b(T - T_0)) + \alpha_1 \times P_{s(B,BO_3^-)_0} \exp(c(T - T_0))$$

Boron reflection coefficient

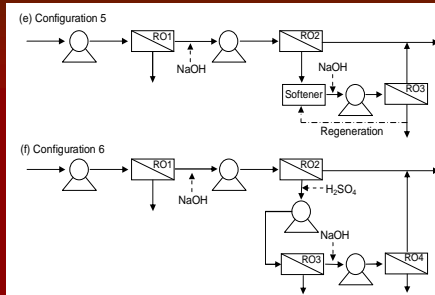
$$\sigma_B = \alpha_0 \times \sigma_{(H,BO_3)_0} ((T - T_0) + c) + \alpha_1 \times \sigma_{(H_2BO_3^-)_0} ((T - T_0) + d)$$

PART III. COST ANALYSIS OF BORON REMOVAL REVERSE OSMOSIS PROCESSES

Representative RO System Configurations



Representative RO System Configurations (Cont'd)



Cost Estimation Method: Capital Cost

System Cost Breakdown

RO equipment cost	Pressure vessel, Membrane element, Trains
Other equipment cost	Pumps, MCC, Controls, Cleaning system, Piping, Permeate post treatment equipment
Pretreatment equipment cost	Chemical dosing system, Filtration system
Site and construction cost	Raw water intake, Feed storage tanks, Site preparation, Buildings and construction
Engineering cost	Construction supervision, Process and system design
Other indirect cost	Financing, Interest during construction

Cost Estimation Method: Capital Cost (Cont'd)

Equipment cost calculation basis

SWRO Pressure vessel	\$2,400/each
SWRO Membrane element	\$550/each
SWRO trains	\$4,440/Pressure vessel
BW RO Pressure vessel	\$1,700/each
BW RO Membrane element	\$550/each
BW RO trains	\$2,910/Pressure vessel
RO pretreatment cost	50 \$/m ³ feed
Ion exchange unit	\$150,000 for 70 m ³ /hr capacity

$\text{Other equipment cost} = 1 \times (\text{Pressure vessel cost} + \text{RO element cost} + \text{RO train cost})$
 $\text{Engineering cost} = 0.2 \times (\text{Pressure vessel cost} + \text{RO element cost} + \text{RO train cost} + \text{RO pretreatment cost} + \text{Site and construction cost})$
 $\text{Indirect cost} = 0.5 \times (\text{Pressure vessel cost} + \text{RO element cost} + \text{RO train cost} + \text{RO pretreatment cost} + \text{Site and construction cost})$
 $\text{Contingency cost} = 0.1 \times (\text{Pressure vessel cost} + \text{RO element cost} + \text{RO train cost} + \text{RO pretreatment cost} + \text{Site and construction cost})$
 $\text{Capital cost} = \text{System cost} \div \text{Yearly capital cost factor (Annuity factor)} \div \text{Time} \div \text{Plant capacity} \div \text{Loading factor}$

Cost Estimation Method: Operation Cost

Operation cost calculation basis

Chemical cost	0.0225 \$ /m ³ treatment of feed
Electricity cost	0.05 \$ / kW-hr
Membrane replacement cost	15 % replacement per year
Maintenance cost	3 % of equipment cost
Labor cost	8 persons, \$30,000 / year / person

$\text{Pumping power} = 0.027 \times \text{Feed Flow} \times \text{Pressure head} \div \text{Pump efficiency} \div \text{Motor efficiency}$
 $\text{Recovered power} = 0.027 \times \text{Flow} \times \text{Pressure head} \times \text{Turbine efficiency}$

Cost Analysis of Representative RO System Configurations

Configuration	1	2	3	4	5	6
SW RO Pressure vessel (ea)	100	100	102	100	104	104
SW RO Membrane element (ea)	800	800	816	800	832	832
BW RO Pressure vessel (ea)			10		42	50
BW RO Membrane element (ea)			80		336	400
Pressure vessels cost(\$)	240,000	240,000	261,800	240,000	321,000	334,600
Membrane elements cost(\$)	440,000	440,000	492,800	440,000	642,400	677,600
RO trains cost (\$)	444,000	444,000	481,880	444,000	583,980	607,260
Other RO equipment (\$)	1,124,000	1,124,000	1,236,480	1,124,000	1,547,380	1,619,460
RO pretreatment equipment (\$)	1,000,000	1,000,000	1,010,101	1,000,000	1,250,000	1,250,000
Site and construction (\$)	1,500,000	1,500,000	1,600,000	1,600,000	1,700,000	1,700,000
Engineering cost (\$)	949,600	949,600	1,016,612	969,600	1,208,952	1,237,784
Indirect cost (\$)	2,374,000	2,374,000	2,541,531	2,424,000	3,022,380	3,094,460
Contingency (\$)	474,800	474,800	508,306	484,800	604,476	618,892
Ion exchange equipment (\$)				150,000		
Total system cost (\$)	8,546,400	8,546,400	9,149,510	8,876,400	10,880,568	11,140,056
	0.227	0.227	0.243	0.236	0.289	0.296

Cost Analysis of Representative RO System Configurations (Cont'd)

Pumping energy (kw-hr/m ³)	2.53	2.53	2.64	2.54	3.16	3.21
Pumping energy + auxiliary power (kw-hr/m ³)	3.03	3.03	3.14	3.04	3.66	3.71
Power cost (\$/m ³)	0.1515	0.1515	0.157	0.152	0.183	0.1855
1st pass chemical cost (\$/m ³)	0.0450	0.0470	0.0455	0.0450	0.0468	0.0468
2nd pass chemical cost (\$/m ³)			0.003	0.007	0.018	0.018
Membrane replacement (\$/m ³)	0.0201	0.0201	0.0225	0.0201	0.0293	0.0309
Maintenance (\$/m ³)	0.0015	0.0015	0.0016	0.0015	0.0020	0.0020
Labor (\$/m ³)	0.0731	0.0731	0.0731	0.0731	0.0731	0.0731
	0.291	0.293	0.303	0.299	0.352	0.356
Water production cost= Capital + Operation cost (\$/m ³)	0.518	0.520	0.545	0.534	0.641	0.652

PART IV. CONCLUSION

Conclusion

- Analysis from nine RO desalination plants suggested that while most ionic species generally showed over 99 % removal, rejection of boron was between 65 and 85 % and largely dependent on membrane type, operating condition and sampling location within the membrane vessel (brine side and feed side)
- Boron rejection performance observed during bench-scale test did not correlate well with the rejection performance observed in the full- or pilot-scale plants and this was mainly due to the higher recoveries used at the full- or pilot-scale plants
- Transport mechanism of boron through the SWRO membranes was different from other ionic species and much influenced by pH. Change of dominant species by pH change account for this phenomenon
- From the non-linear parameter estimation method combined with experimental calculation of mass transfer coefficients, parameters in Spiegler-Kedem model with Film theory were successfully estimated

Conclusion (Cont'd)

- Spiegler-Kedem model coupled with Film theory could accurately predict the boron transport through SWRO membranes tested
- pH and temperature dependency of boron transport parameters was investigated and the equations to predict the transport parameters at different pH and temperature condition were developed
- A single-pass RO system with increased feed pH (Configuration 2), a partial double-pass RO (Configuration 3), and a single-pass RO system with IX polishing (Configuration 4) could produce permeate containing <1 mg/L of boron, but Configuration 2 cost 0.520 \$/m³ (1.96 \$/ 1000 gal) and was the most cost-effective option, with very slight increased water production cost from the Configuration 1.
- To meet the provisional WHO boron guideline of 0.5 mg/L, double pass RO with a concentrate recovery system was required. However, these configurations would be approximately 20 to 25 % more expensive than other configurations.